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ON REALISTIC BRANE WORLDS FROM TYPE I STRINGS[a]

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We review recent progress in constructing realistic brane models from type I string vacua. Explicit models with three families of the standard model gauge group and its left-right generalizations are presented with supersymmetry broken at the string scale of order $M_s \sim 10^{10-12}$ GeV, realizing gravity mediated supersymmetry breaking at low energies. Unification of couplings occurs at the string scale due to the particular $U(1)$ normalizations of D-branes, as well as to the existence of a Higgs field per family of quarks and leptons. The proton is naturally stable due to intrinsic discrete symmetries of the corresponding string theory. In particular R-parity appears as a natural stringy symmetry. There are axionic fields with the right couplings as to solve the strong CP problem. Similar realizations are also presented for a string scale of 1 TeV, although without solving the gauge unification problem. Open questions are briefly discussed.

1 Introduction

The present understanding of string theory indicates that all the different 10-dimensional string theories (types I, IIA, IIB and two heterotic) happen to be different manifestations of a single M- theory. It has also led to a prime role played by high dimensional surfaces known as D-branes, giving support to the idea that our 4-dimensional world could itself be a brane.

The brane world scenario has been subject to intense investigation during the past two years and new interesting mechanisms have been proposed to solve longstanding problems with the standard model, such as the hierarchy problem,

[a] Plenary talk by FQ at PASCOS 99

gauge coupling unification, neutrino masses, strong CP problem, etc. One of the interesting properties of this scenario is that it allows for a fundamental scale of nature to be much below the Planck scale and therefore closer to experiments [1] . However until recently explicit realizations of this scenario, with low-energy fundamental scale, were lacking. We review here the progress we have made in that direction during the past few months.

Since this is the first talk of the meeting we have to briefly review the idea of the brane world scenario. This is a variation of a Kaluza-Klein theory for which the extra dimensions are felt only by a subset of the fields. The typical case is that the Standard Model fields are constrained to live inside a low dimensional surface, or brane, of the high dimensional spacetime, but gravity lives in the full spacetime [2]. This seems like a *ad-hoc* separation of the fields, however recent developments on string theory precisely point at this scenario. The Horava-Witten realization of strongly coupled heterotic string, leads after compactification, to a 5D world with the 5th coordinate being just an interval. Gauge and matter fields live only on the two 4D surfaces at each end of the interval, whereas gravity lives in the full 5D spacetime. Similarly, and more relevant for this talk, type I string theory includes Dp-branes. These are surfaces where the end points of the open strings are attached, satisfying Dirichlet boundary conditions, here the origin of the name D-branes. The surfaces may be of different dimensionality which is denoted by p. Each Dp-brane has a $U(1)$ gauge field corresponding to an open string with both endpoints on the same brane. There are also states corresponding to open strings with endpoints on two different branes, the mass of these states is proportional to the distance between the branes, therefore when two branes overlap, the distance vanishes and these states become massless with the net effect of enhancing the gauge symmetry from $U(1)^2$ to $U(2)$. If there are N overlapping branes the gauge symmetry will then be $U(N)$. On the other hand, gravity corresponds to closed strings and these can move on the whole 10-dimensional spacetime. Therefore we have a clean realisation of the brane world scenario in type I string theory with $U(N)$ (or other groups) living on the brane and gravity on the bulk.

2 Brane World versus Kaluza-Klein

It is important to realise the difference between the brane world and the better known Kaluza-Klein scenario. In Kaluza-Klein all fields feel the extra dimensions whereas in the brane world, only a subset of the fields (gravity and moduli fields in string theory) feel all the extra dimensions.

This simple fact has very important physical implications regarding the possible values of the fundamental scale. An explicit way to see the difference

is comparing the low-energy effective actions for perturbative heterotic strings and type I strings. In the heterotic case, both gravity and the gauge fields live on the full 10-dimensional spacetime corresponding to a standard Kaluza-Klein scenario. The low-energy effective action in 10 dimensions takes the form:

$$S \;=\; M^8 \int d^{10}x\sqrt{-G}\; e^{-\phi}\left(\mathcal{R} \;+\; M^{-2}\; F^2_{MN} \;+\; \cdots\right), \tag{1}$$

where $M = 1/\sqrt{\alpha'}$ is the string scale and ϕ is the dilaton field. Upon compactification to 4-dimensions each of the two terms in the action above will get a volume factor coming from the integration of the 6 extra dimensions. This gives us an expression for the gravitational and gauge couplings (the numerical coefficients of each of the two terms above) of the form:

$$M^2_{Planck} \;\sim\; e^{-\phi}\; M^8 r^6 \qquad \alpha^{-1}_{GUT} \;\sim\; e^{-\phi} M^6 r^6 \tag{2}$$

where r is the overall size of the extra dimensions. Taking the ratio of those expressions the volume factors cancel and we get $M^2_{Planck} \sim \alpha^{-1}_{GUT} M^2$. Therefore for α_{GUT} not much different from 1 (as expected) we have to have the fundamental scale M to be of the same order of magnitude as the gravitational scale $M_{Planck} \sim 10^{19}$ GeV. This was the old belief that the string scale was the Planck scale.

Things are very different in the brane world scenario as we can see for the case of the type I string. For a configuration with the standard model spectrum belonging to a Dp-brane, the low energy action in 4-dimensions takes the form:

$$S \;=\; -\frac{1}{2\pi}\int d^4x\sqrt{-g}\left(r^6\; M^8\; e^{-2\phi}\mathcal{R} \;+\; \frac{1}{4}(rM)^{p-3}\; e^{-\phi}\; F^2_{\mu\nu} \;+\; \cdots\right) \tag{3}$$

Comparing the coefficient of the Einstein term with the physical Planck mass M^2_{Planck} and the coefficient of the gauge kinetic term with the physical gauge coupling constant $\alpha_p(\sim 1/24$ at the string scale), we find the relation:

$$M^{7-p} \;=\; \frac{\alpha_p}{\sqrt{2}}\; M_{Planck}\; r^{p-6} \tag{4}$$

from which we can easily see that if the Standard Model fits inside a D3-brane, for instance, we may have M substantially smaller than M_{Planck} as long as the sizes of the extra dimensions are large enough.

Given the fact that we do not have a way to fix the size of the extra dimensions we can take advantage of our ignorance and follow a bottom-up approach considering different possibilities motivated by phenomenological inputs. Several scenarios have been proposed depending on the value of the fundamental scale. The four main scenarios at present correspond to

1. $M \sim M_{Planck}$. This is just the old perturbative heterotic string case corresponding to compactification scale close to the Planck scale. There is nothing wrong with this possibility [3]. Research over the years has shown difficult to obtain gauge coupling unification in this case.

2. $M \sim M_{GUT} \sim 10^{16}$ GeV. Obtained for $r \sim 10^{-30} cm$ in the expression above. This proposal [5] was made precisely to 'solve' the gauge coupling unification problem in string theories. This requires a compactification scale of order 10^{14} GeV. Recent progress has been made [4] in looking for three generation models realising this scenario from the Horava-Witten construction but, so far, not from type I models.

3. $M \sim M_I \sim 10^{10-12}$ GeV. If the world is a D3-brane we can see that this scale is obtained from the equations above for $r \sim 10^{-23} cm$. This proposal [6], was based on the special role played by the intermediate scale M_I in different ideas beyond he standard model. Particularly the scale of supersymmetry breaking in gravity mediated supersymmetry breaking scenario. This then allows to identify the string scale with the supersymmetry breaking scale and opens up the room for non supersymmetric string models to be relevant at low-energies. Explicit models realising this scenario will be discussed in the next section.

4. $M \sim M_{EW} \sim 10^3$ GeV. This is obtained for overall radius $r \sim 10^{-12} cm$ above and if only two of the six dimensions were large this would have given us the famous $r \sim 1mm$ quoted as the extreme case of the brane world scenario since lengths bigger than this would have been observed by deviations of gravity. This is the most popular scenario [7] due to its proximity with experiment. Concrete string models realising this scenario do not exist. We will discuss some attempts in the next section.

Notice that only the first scenario was possible following the standard Kaluza-Klein approach in the perturbative heterotic string models. The brane world opened up the possibility of the next three scenarios as well as any other scale in the range $M_{EW} < M < M_{Planck}$.

3 String Model Building

In order to construct realistic string models, starting from 10 (or 11) dimensions we have to specify the nature of the extra 6 or 7 dimensions. The simplest idea that comes to our mind is to set the extra dimensions to be circles or tori, since they are still flat, however the 4-dimensional models obtained in this way

are not chiral for any string theory and therefore cannot describe the standard model.

In the 80's this was solved by either assuming that the extra dimensions were a compact Calabi-Yau space or an orbifold limit [8]. An orbifold is a twisted torus. The simplest example is the one-dimensional interval which can be considered as a twisted circle in the following way: defining the circle as the set of all the points in the real line identified by a $2\pi r$ shift, *ie* $X \equiv X+2\pi r$, we can now twist the circle by further identifying the points $X \equiv -X$, which leaves us only with the interval $[0, \pi r]$. The two end points of the interval are fixed points under the orbifold identification and represent 'singular' points of the space. This is then a Z_2 orbifold in one dimension. A generalization to 6 dimensions in terms of more general discrete twists defines good compactifications of string theory.

There are many possible string vacua constructed this way, they are determined by the different allowed twists of six-dimensional tori, the way this twists acts on the gauge degrees of freedom and the addition of nontrivial gauge background fields on the noncontractible loops of the defining tori. These 'Wilson lines' are the main source for the huge degeneracy of this class of string vacua [8].

Explicit orbifold models were constructed in the past starting from the heterotic string, exhibiting many features similar to the standard model (same gauge group, three families, structure of Yukawa couplings, etc.) [8] and new constructions are still being worked out [3]. The orbifold construction has the advantage over Calabi-Yau manifolds of being essentially a flat space, except for a few special points and still allowing chiral 4-dimensional models and therefore it is possible to describe string interactions in such a background. It is worth mentioning that these compactifications singled out the heterotic string as the most viable string theory since it was the one for which it was possible to obtain chiral models with realistic properties.

4 Realistic Type I Brane Models with Broken SUSY

After the introduction of D-branes, the perspective about type I models has changed completely. It allows us to look for the standard model not only inside the 'bulk' 10-dimensional spacetime but also inside some of the lower dimensional D-branes that appear in such vacua.

Much work has been devoted recently to the construction of 4-dimensional type I models. A particularly useful way to build open type I string models is to start with closed type IIB strings and perform a kind of orbifold twist on the (2-dimensional) string worldsheet identifying the two orientations of type IIB

strings, this is called an 'orientifold'. On top of this, compactifications similar to those of the heterotic string in terms of orbifolds have been obtained, classified by the different twists and background gauge fields or Wilson lines. The net result of this investigation is that although similar to the heterotic strings, many chiral models can be constructed preserving $N = 1$ supersymmetry, none of them can be claimed to be close to the Standard Model.

One of the reasons for this lack of realistic models is the fact that there are consistency conditions that the models have to satisfy in order to avoid unwanted tadpoles (which if existing would give rise to anomalies in the 4-dimensional theory). These tadpole cancellation conditions happen to be more restrictive than the corresponding conditions in the heterotic case and therefore there is less room for realistic models.

In order to obtain realistic models we may relax the conditions we had imposed on the models, in particular we may look for models without supersymmetry. Notice that this possibility was not open to us in the heterotic case because constructing a nonsupersymmetric model at the Planck scale would leave us without a solution to the hierarchy problem. As argued in the previous section, in type I models we may have the string scale lower than 10^{12} GeV. In this case having a nonsupersymmetric model may still solve the hierarchy problem at low energies as long as we have gravity mediated supersymmetry breaking in the visible sector of scenario 3. above, for which the splitting in multilplets will be of the order $M^2/M_{Planck} \leq 1$ TeV. On scenario 4. we may just have explicit supersymmetry breaking without any danger. Therefore in nonsupersymmetric brane models are now an interesting alternative to the supersymmetric string vacua.

A concrete way to build nonsupersymmetric brane models is to look for string vacua including both branes and antibranes. It is known that a brane, being a BPS state, breaks partially supersymmetry, an anti-brane breaks the remaining supersymmetry so the configuration brane/anti-brane is non supersymmetric. However brane/anti-brane configurations tend to be unstable which usually shows in the appearance of tachyons in the spectrum. In orbifolds of type I models this can be avoided by having the antibranes of different dimension than the branes which then do not annihilate each other. Furthermore, tadpole cancellation conditions force some of the branes or anti-branes to be trapped in some of the orbifold fixed points avoiding the annihilation of branes and anti-branes of the same dimensionality.

We can then envisage models with,for instance, D7-branes with D3-branes trapped at some of the orbifold fixed points and some anti D3-branes trapped at different orbifold singularities which cannot annihilate each other. Models of this type have been explicitly constructed recently [10,11] with the following

physical properties:

1. On the D7-branes there is the gauge symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$ or its left-right extension $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ the matter sector includes three families of quarks and Higgs fields.

2. On the trapped D3-branes and anti D3-branes there are extra gauge fields which for the D3 case are broken by some flat directions in the model. The three families of lepton fields appear as open strings with one endpoint on a D3-brane and the other on the D7-brane.

3. The presence of 'hidden' anti-D3-branes explicitly break supersymmetry, but its breaking is felt by the visible sector only through gravitational strength interactions. Therefore if the string scale is the intermediate scale this would correspond to the gravity mediated supersymmetry breaking scenario. If the anti-D3 branes happen to be inside the D7-branes then the breaking of supersymmetry is explicit and a TeV fundamental scale is required.

4. The D-brane origin of the $U(1)$ gauge groups fixes the hypercharge normalization to be $3/14$ different from the $3/8$ of $SO(10)$ GUTs. Furthermore the appearance of three rather than one families of Higgs fields change the RG running of the couplings in such a way that unification occurs at the intermediate scale $M \sim 10^{11}$ GeV. This is particularly realised in the left-right models for the scale of $SU(2)_R$ breaking close to 1TeV, having then important experimental consequences at present and future collider. The 1TeV scenario fails to satisfy the gauge coupling unification in this class of models.

5. Yukawa couplings providing structure of quarks and lepton masses (including neutrino masses) can be obtained from the the superpotential. Their full understanding requires also knowledge of the Kahler potential which is not under complete control.

6. The particular way that the three lepton families are distributed among the branes gives rise to discrete versions of lepton number as exact symmetry of the models. Further discrete symmetries obtained from the structure of the original flat directions, give rise naturally to R-parity as an exact discrete symmetry forbidding fast proton decay.

7. There are particular (Ramond-Ramond) axion fields at the singularities with the properties and couplings needed to solve the strong CP problem. This depends crucially on the fact that the fundamental scale is intermediate. This was not possible in the old heterotic models.

8. The explicit potential for the scalar fields is not known and the minimisation process cannot be performed at present. It is yet to be seen that this stabilisation could fix the value of the compact space to the 'right value' as to obtain the intermediate fundamental scale and the even most difficult requirement of generating a very small cosmological constant which is not protected after supersymmetry was broken. These are left as open questions for the moment.

These are exciting times for string model building.

1. See contributions of Antoniadis, Dienes and Dimopoulos and references therein.
2. For a mechanism where gravity is also localised see the contributions of Lykken and Csaki and references therein.
3. See contributions of A. Faraggi and G. Cleaver.
4. B.A. Ovrut, hep-th/9905115 and references therein.
5. E. Witten, *Nucl. Phys.* **B471** (19135) 1996.
6. K. Benakli *Phys. Rev.* **D60** (19104002) 1999; C.P. Burgess, L.E. Ibáñez and F. Quevedo, *Phys. Lett.* **B447** (19257) 1999.
7. J.D. Lykken, *Phys. Rev.* **D54** (193693) 1996; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, *Phys. Lett.* **B436** (19257) 1998.
8. For a review with many references to pre 1994 works see F. Quevedo, hep-th/9603074.
9. I. Antoniadis, E. Dudas and A. Sagnotti, hep-th/9908023; G. Aldazabal and A. Uranga, hep-th/9908072.
10. G. Aldazabal, L. Ibáñez and F. Quevedo, hep-th/9909172; JHEP 01 (2000) 031.
11. G. Aldazabal, L. Ibáñez and F. Quevedo, hep-th/0001083; JHEP 02 (2000) 015.